EXPERIMENTAL STUDIES OF THE EJECTA VELOCITY DISTRIBUTION FROM OBLIQUE IMPACTS: TOWARDS AN ANALYTICAL MODEL

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Introduction and Background: Impacts on planetary surfaces occur almost exclusively at oblique angles [1, 2]. Generally, the shape of the final crater retains circularity for all but the lowest angle impacts, and vertical incidence is often assumed to greatly simplify the dynamics. This permits the application of canonical scaling laws (e.g., [3]) to infer characteristics of the event, such as ejection velocities and blanket thicknesses. The ejecta distribution deposited on the surface, however, belies the obliquity of the impact at both laboratory and planetary scales [4, 5]. The early-time regime, while the projectile is still coupling its energy and momentum to the target, affects the emplacement of distal ejecta and plays a greater role at larger planetary scales. The early-time processes are especially apparent in oblique impacts because the zone of coupling is extended laterally along the impact trajectory. Effects include a downrange focusing of material and an uprange "zone of avoidance." To date, no simple physically based analytical ejection velocity model incorporating impactor obliquity has been proposed.

In this study, we present results from new high-speed experimental studies performed at the NASA Ames Vertical Gun Range (AVGR) designed to measure the effect of obliquity on the ejecta velocity distribution for impacts over a range of incidence angles. These data provide a temporally resolved view of the ejecta evolution for the first time, and allow development of an analytical description of the velocity distribution as a function of time and azimuth (rather than launch position, which requires complicated correction terms [6]).

Background: Ejection velocities during main-stage excavation flow have been well studied for vertical impacts in granular materials through dimensional analysis [3] and numerous experimental and computational approaches [7, 8, 9, 10, 11, 12, 13]. When the axisymmetric simplification of vertical incidence is removed, the complexity of the ejection process increases significantly. Asymmetries in the shock from oblique impacts are manifested in azimuthally dependent velocities and ejection angles in the ejecta flow-field.

Previous studies have examined oblique impact ejecta distributions from the ballistic deposition of material on the surface [4] and ballistic capture in discrete azimuths [14]. Anderson and Schultz presented pioneering experimental studies of the oblique ejecta velocity distribution utilizing a particle imaging velocimetry technique to capture the three-component velocity of groups of particles over all azimuths [11]. The measurement captured a single discrete velocity vs. launch position data point (for all azimuths) per impact experiment, and was not designed to be temporally resolved.

Experimental Methodology: In order to address and constrain the effects of oblique impact conditions on the early-time ejecta distribution, a suite of impact experiments into #20-30 sand was carried out at the AVGR. Here we present the results from 30°, 45°, 60°, and 90° hypervelocity (∼ 5km/s) impacts of a 6.35mm aluminum projectile. The technique employed in this study is an outgrowth of the initial work at the AVGR by [6, 11, 15]. The method developed for this application (High-Speed Two-Frame Hybrid 3-Dimensional Particle Tracking Velocimetry, or "3D-PTV" in this work) appears qualitatively similar to the experimental setup previously employed by Anderson and Schultz, but the measurement is inherently different due to the requirements of the high-speed the dataset needed for temporal description.

The 3D-PTV system utilizes a pulsed laser light sheet projected parallel to the impact surface to illuminate horizontal slices of the ejecta curtain (see Fig.1), which are then recorded by cameras. The locations of individual particles are photogrammetrically determined and tracked in subsequent frames in a Lagrangian fashion to determine velocities (see Fig. 2 for example images).

Results and Analysis: Ejection velocities are presented as a function of time and azimuth (as presented in Fig. 3). In this study, we adopt a cylindrical coor-

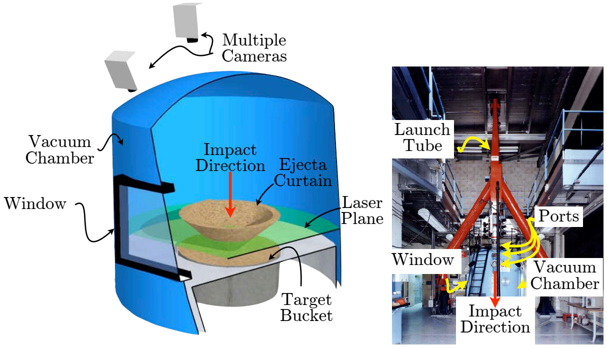

Figure 1: Schematic of experimental setup (left) and photo of AVGR (right). A laser light sheet is projected into the chamber parallel to the target surface to illuminate cross-sectional wedges of the ejecta curtain. High-speed cameras view the impact from above through windows in the vacuum chamber.

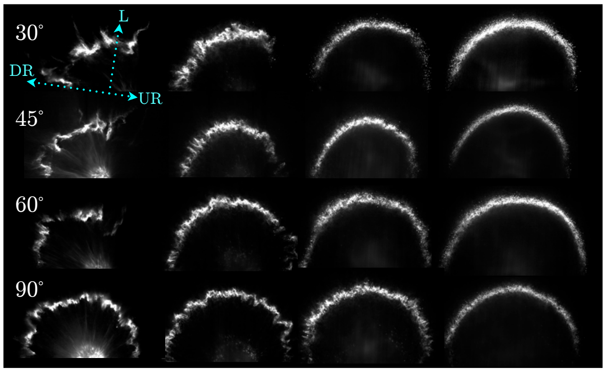

Figure 2: Cross-sectional ejecta comparison for different impact angles. Each row corresponds to an experiment; images are dewarped and selected for approximately equal τ. Downrange is to the left; uprange is to the right. Images display only one half of the curtain. The oblique impacts show the delay in arrival of the uprange ejecta; the 30° case maintains asymmetry for much further into crater growth than the other impacts. Early-time ejecta is characterized by sparse, crushed material that evolves into main-stage behavior.

dinate system, where the ejection velocities are defined by time of launch t, azimuth ϕ, and radial and upward velocity components. The azimuth convention adopted here defines downrange (in the direction of the impactor) as 0° with uprange at 180°; the "lateral" component is taken at 90°. Separation of the velocities by component as a function of azimuth at discrete times provides further insight into the ejection process. The radial velocity component is found to exhibit a sinusoidal dependence on azimuth that decreases in asymmetry with time and is seen less in higher angle impacts. An enhancement in velocities (and thus lower ejection angles) is apparent in the downrange direction. A physical model based on the energy and momentum coupling in the impact can be fit to these data to develop a metric to scale the velocities in oblique impacts in a similar manner to those widely employed for vertical incidence.

Conclusions and Implications: The high temporal resolution of this study allows a physically based temporal description of the ejecta velocity distribution for oblique impacts for the first time. In the downrange direction, the initial momentum partitioning is retained in the target, visible in an enhancement of high speed material early in the process. The radial component exhibits a sinusoidal dependence on azimuth, expressed by a velocity enhancement in the downrange direction and a reduction in the uprange side. The value in point-source ejecta models is that they provided a simple metric for ejecta scaling. The model developed here delivers a similar tool for oblique impacts based on the initial conditions of the event. The temporal nature of these data allow this description in time, and removes the dependence on the spatial domain. Further study of the effect of different impact variables will constrain the early-time component and ultimately allow scaling to planetary events. With increasing crater size, early-time processes encompass a greater percentage of crater growth [5, 16]. The evolution of the ejecta distribution is essential for interpretation of impact mission results (such as the Deep Impact mission) and can be used to map out the ejecta distribution on planetary bodies.

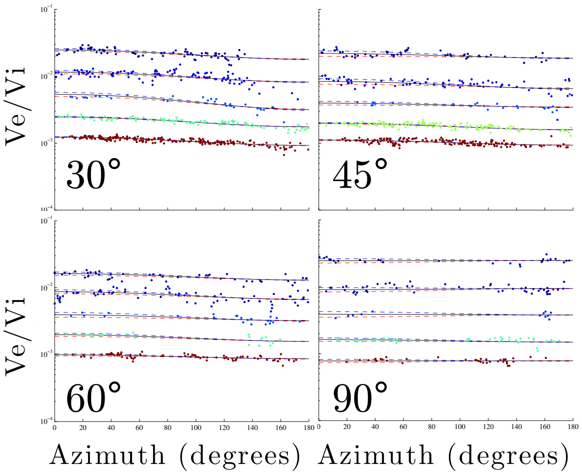

Figure 3: Radial ($in - plane$) velocity measurements for 30°, 45°, 60°, and 90° impact experiments as a function of azimuth at selected times after impact. The fit line for the data (black), and confidence intervals (blue and red dashed lines) are overlaid. The ordinate axis is presented logarithmically to allow display of the large differences in velocities for different times. As a result, the variance with azimuth visually appears to have only a small effect even though it actually represents a $\sim 50\%$ difference in radial velocity between downrange and uprange components for early-time ejecta from the 30° impact.

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